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Interactive comment on “Regionalization of turbulent fluxes by combining aircraft measurements with footprint analysis” by T. El-Madany et al.

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Dear Referees, thank you for the supportive ideas and the constructive feedback. They helped to improve the quality of this paper and sharpen important aspects. In the following we are going to answer the major questions and comments and give an overlook how we adopted your comments into the manuscript.

Referee 1:

1) The authors emphasize the importance of footprint analysis, yet the presented discussion is mostly limited to footprint models used for the surface layer. Some of the presented airborne observations were also conducted in the mixed layer. Specific footprint

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models that have been developed for mixed layer applications need to be addressed in more detail. It is questioned whether surface layer scaling can be applied in all cases.

To our knowledge there is no footprint model which was built to be used for airborne measurements. Thus we looked for a footprint model which can be evaluated for its suitability for airborne measurements. The Analytic footprint model (AFPM) is implemented into a footprint tool (FPT) as described by Neftel et al. (2001) that has two features that demand our needs: It is capable to produce thousands of footprints in a short time and, more importantly to us, it can calculate the contribution of predefined areas to the footprint. With these features, it is possible to break a footprint down into smaller areas which help to evaluate the suitability of the AFPM in an inhomogeneous landscape. Single landscape elements and their contribution to the footprint can be estimated and thus be used to evaluate the suitability of the footprint model for airborne measurements. The AFPM was created for homogeneous surfaces and measurements in the surface layer. Nevertheless we tested the suitability of the model for airborne measurements and found good agreement between the land use inside the footprint areas and the measured flux pattern as detected on the aircraft. Another footprint model that seems to be well suited for airborne measurements is described in Kljun et al. (2002) A comparison with this model and using our data will be done soon (if funded) and we expect that model to produce excellent results as well. For the moment, such a comparison was beyond the scope of this paper. We added the following part to the conclusion part A comparison to other footprint models would help to find which footprint model is best suited for airborne measurements. The Lagrangian backward model by Kljun (2002) would be an eligible candidate for such a comparison. Since the model can be used for a wide range of atmospheric stratifications and measurement height.

2) The concept of mapping measured fluxes on such a heterogeneous landscape seems to be significantly challenged by the fact that no significant correlation between measured fluxes and landsurface classes is observed (e.g. figure 9).

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We agree with the reviewers comment that one should expect to find a correlation between the land use types and the corresponding flux. However, it must be recognized that the flux as measured on the aircraft is a result of the different land use types inside the total footprint. Therefore a total footprint with, e.g., 45 % forest coverage does not necessarily lead to a more negative flux of CO₂ than a footprint with just 5 % forest. The reason is that the footprint with the 45 % of forest may also include urban areas with high CO₂ production which countervail the CO₂ uptake of the forest area. We are able to determine clear correlations between land use and airborne measured fluxes on a scale of few single footprints as shown by the evaluation of the suitability of the footprint model, but not for an entire flight segment. We added the example above to the text to make it more clearly for the reader.

3) The analysis of separate small flux segments is questionable without further analysis to support the idea that these fluxes are meaningful for interpreting surface fluxes.

The analysis of small flux segments (flux events) is just used for the evaluation of the footprint model because they can easily be correlated to certain land use types. These small segments have a certain contribution to the measured flux.

4) There is no discussion about stationary criteria, which can pose problems in such a heterogeneous landscape and at such low flight levels. In particular Fourier transformation can suffer because it is based on the ergodic hypothesis.

We added the following part to section 2.9: Furthermore stationary was tested by dividing the flight segments into sub segments of 25 seconds and comparing the means of the sub segments with the total segment. If the difference between the sub segment and the total segment is less than 50 % the time series is said to be stationary. Flight segments with higher differences were excluded from further calculations.

5) P 7023: Rather than speculating about appropriate length scales, co-spectral analysis is necessary to show over what length scales fluxes should be investigated. A periodogram of vertical wind speed (fig 11) is simply not sufficient. More detailed anal-

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ysis on cospectra would be required.

A co-spectral analysis was done and implemented into the text as follows: A co-spectral analysis (MATLAB Mathworks) showed, that regardless of the flight length, eddies of 1000-2000 m size are responsible for the large portion of the CO₂ flux whereas sensible heat- and water vapor are mainly transported by eddies in a size range of 250-800 m (Figure 11). Consequently the shorter segments do not miss components that the longer segments detect. The averaging length of the flight segments used for the flux calculation seems therefore adequate. The co-spectral analysis also indicates that large transport structures in the low frequency end of the spectrum are not fully covered, even by the long segments. The maxima of the co-spectral curves are detected though. To catch those structures in full extend, the flight segments would have to longer by about an order of magnitude than the flights preformed.

6) P7023: here, the authors worry about artificial fluxes evoked from height gradients of scalars. If this is expected to be a significant issue, the authors need to investigate the influence of vertical flux divergence of various scalars (e.g. NO₂).

Vickers and Mahrt (1997) and Mahrt (1998) mention that vertical gradients of scalars can lead to artificial fluxes. On the one hand we used leveled flights to avoid the risk of dealing with such vertical gradients and on the other hand we know from vertical profiles which were flown before and after every measurement flight that the atmosphere was well mixed. As a result we can assume that we have no problem with artificial fluxes of this kind.

7) P7031 (line 5). This sentence is confusing and somewhat misleading: if the same 70 Km² are repeatedly sampled I don't see how it can be argued that the total sampled area is so much larger (e.g 4 times 1510 km²), since large scale flux contributions might still be comparably small.

The text was changed for clarification: The sample area (the area that contains all total footprints of the 86 flight segments) is 1510 km² in size. Due to repetitive flight

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patterns the area of the 86 total footprints is more than 4 times larger than the sample area which will be referred to as the “Münsterland”.

Referee 2

1) As mentioned by the authors in Section 2.1, cloud cover varied during the flights between 1/8 and 6/8. Hence, photosynthetically active radiation (PAR) must have varied significantly. Variability in PAR certainly had an impact on CO₂ and H₂O fluxes. However, it is not clear how the authors accounted for this impact, i.e. how it was separated from the flux changes due to different sources (vegetation types).

The cloud cover varied during the measurement period but during the single measurement days the cloud cover was relatively constant. We changed the text in the manuscript to make that clearer.

2) From the description of the footprint tool used in this study, it is not clear how the surface conditions were taken into account. The authors mention that “The large standard deviation of the observed fluxes reflects the inhomogeneity of the surfaces with different compositions of vegetation, water surfaces, and urban areas.” (P7031). Is the model valid for heterogeneous surfaces as encountered in this study?

The model was created for homogeneous surfaces. However, we showed through evaluation of the flux events that the model recognizes the contributions of patches of the surface to the measured fluxes. Overall, i.e. for an entire flight segment, many different patches with different surface characteristics contribute to the total flux. Therefore, individual landscape elements do not show in the total flux very distinctly. This is the result of the heterogenic landscape.

3) P7019, L8ff: The list of fluxnet networks is not exhaustive but implies to be so.

Text adapted as follows: Worldwide measurements have been established in the FLUXNET network (<http://www.fluxnet.ornl.gov/fluxnet>) to quantify the energy and mass exchange between different vegetation types on the one hand and the atmo-

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sphere on the other.

4) P7019, L21: Observations from flux towers are only representative for the surrounding vegetation type AND the surrounding topography.

Adopted the text accordingly

5) P7020, L22: Depending on the atmospheric stability conditions, the area underneath the tower might actually contribute to the measurement.

Adopted the text accordingly

6) P7020, L28: In addition to meteorological conditions, surface conditions will also affect the footprint extent.

Adopted the text accordingly

7) P7021, L4: There's no such a thing as a backward analytical footprint model. With the Lagrangian stochastic approach, footprints may be calculated from "forward" or "backward" simulations. The text was changed: There is a variety of models employing analytical (Horst, 2001; Kormann and Meixner, 2001), large-eddy simulation (Leclercq et al., 1997) and Lagrangian stochastic (Kurbanmuradov and Sabelfeld, 2000; Lee, 2003 Kljun et al) approaches.

8) P7021, Section 2.1: Please describe the spatial variability of the parameters.

Text was adapted: For single measurement days the meteorological parameters were relatively constant. Since the terrain of the investigated area is very homogeneous there was not a lot of spatial variability in the meteorological parameters.

9) P7023, L7: Please clarify: mean over which time period?

Text was adapted: F is the flux of a scalar, w the vertical wind speed, the scalar of interest, the prime denotes a deviation from the mean and the overbar indicates a mean over the measured time period.

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10) P7024, L22: Clarify what you mean by “1% isopleth”.

Text was adapted: The footprint is represented by the area of an ellipse that is an approximation of the total area within the 1 % isopleths of the maximum of the integrated footprint function (Neffel et al., 2008). At this isopleths, the integrated footprint function drops below 1% of its maximum value.

11) P7024, Section 2.5: Please explain the concept of a “total footprint” in more detail. I would expect a total footprint to represent the source area of the averaged flux measurement, i.e. for 4 km length of the flight line. However, this would not match Fig. 1B.

Your idea of the total footprint is absolutely correct. We changed the text of Fig. 1 and hope it is clearer now. Figure 1. A) Land use map with all footprints (beige colored ellipses) of the flight segment. Together they build the total footprint. The black polygon represents the total footprint of the right side, which was calculated from the ellipsis data of the left side. B) The interpolated, spatial information of the flux contribution of the total footprint from figure A. Colors represent the contribution of areas inside the footprint to the measured flux (from red (20 %) to blue (1 %) decreasing). The flight track of the aircraft is symbolized by a red line that is located above the footprint and orientated from west to east.

12) P7027, Section 2.8: Is the information from the land use data weighted by the footprint function?

No

13) P7029, Section 3.1: Instead of $w'C'$, do you mean w_0C_0 ?

In this section the time series of the flux event are described. Due to the short time span, just 2 to 4 seconds, the covariance was used which is not averaged.

14) P7033, Conclusions: The upscaling exercise should be part of the results section rather than the conclusion. Given the high uncertainty (>50%), these results should be

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used only very carefully.

The up scaling exercise is now part of the results. We think that our results are not over-interpreted in the manuscript.

15) P7041, F1: Not clear where sensor/flight track is located.

We added an explanation to the subscription of Fig. 1

16) P7044, F4: Please plot mean wind direction.

Plotting the wind direction with an arrow and text lets the figure look crowded and is somewhat confusing in combination with the north arrow. We prefer to leave it out

17) P7047, F7: Specify r^2 .

We added a linear trend line to the plot and added the value of r^2 .

18) P7049/50, F9 & 10: Please describe the figures in more detail. Are the correlations from land use types within the footprints only? If so, wouldn't you expect significant correlations?

We agree with the reviewers comment that one should expect to find a correlation between the land use types and the corresponding flux. However, it must be recognized that the flux as measured on the aircraft is a result of the different land use types inside the total footprint. Therefore a total footprint with, e.g., 45 % forest coverage does not necessarily lead to a more negative flux of CO₂ than a footprint with just 5 % forest. The reason is that the footprint with the 45 % of forest may also include urban areas with high CO₂ production which countervail the CO₂ uptake of the forest area. We are able to determine clear correlations between land use and airborne measured fluxes on a scale of few single footprints as shown by the evaluation of the suitability of the footprint model, but not for an entire flight segment.

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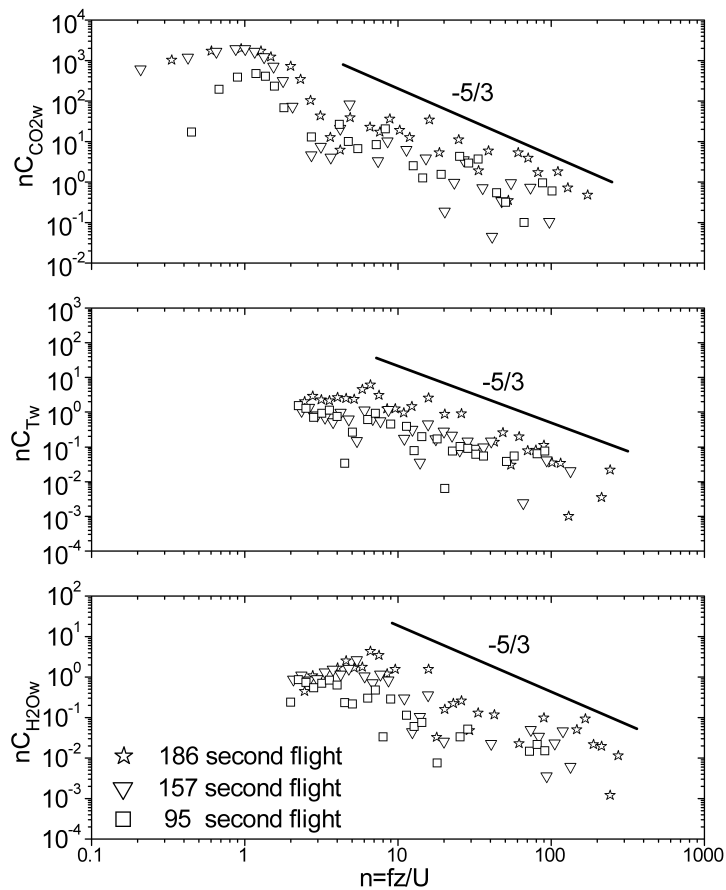


Fig. 1. co-spectra